Application of Hilbert-Huang Transform in the Field of Power Quality Events Analysis

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***Abstract*—This paper deals with the analysis of PQ abnormalities using Hilbert–Huang Transform (HHT). HHT can be applied to both non-stationary as well as non-linear signals and it provides the energy-frequency-time representation of the signal. HHT is a time–frequency analysis method having low order of complexity and does not include the frequency resolution and time resolution fundamentals. So, it has the potential to outperform the frequency resolution and time resolution based methods. Several cases have been considered to present the efficiency of HHT. For the case study, various PQ abnormalities like voltage sag, swell and harmonics with sag are considered. These PQ abnormalities are subjected to HHT and the results are shown in the form of IMFs, instantaneous frequency, absolute value, phase and Hilbert Huang Spectrum. The results shows that the HHT performs better than the any other time resolution and frequency resolution based methods.**

***Index Terms*—Power Quality Events, Hilbert–Huang Transform, Energy–Frequency–Time Distribution.**

I. Introduction

Worldwide utilities have gone through extremist changes from the past two decades [1]-[2]. Therefore, in modern power industry, PQ abnormalities have become one of the most critical and urgent issues. Lightning strokes, electromagnetic transients and the switching of end-user equipment mainly deteriorate the power quality. As they cause distortion in phase, frequency and amplitude of power signal. Revenue of many industries may get affected by such disturbances which are referred to as power quality problems. Steady-state and short duration disturbances are the two main classes of power quality problems. Voltage sag, voltage swell, transient, interruption, sag with harmonics, swell with harmonics comes into the category of short duration disturbances. Voltage flicker, Flicker, Flicker with harmonics, etc. and these type of disturbances are short-term under or over-voltage if that can last from one cycle to several cycles of the 50 Hz AC mains signal. Disturbance signals like noise, flicker, harmonics, inter-harmonics, notch, chirp increasing and decreasing, etc. are categorized under steady state disturbances [3]. For automatic detection and classification of different types of power quality problems, a number of techniques have been investigated in [4]-[6].

Analyzing these power signal disturbances and for distinguishing their pattern, advance signal processing techniques plays an important role. Traditionally, Fourier transform (FT) was the mostly used tool for analyzing the frequency contents of the signal but alone FT is not enough for extracting the features because of the transient nature of most power quality signals where time domain is required for analyzing these signals. In [7] authors proposed FFT based approach for analyzing the power quality disturbances. But FT is able to analyze the stationary information of PQ events. To overcome the inadequacy of FT, short-time Fourier transformation (STFT) is adopted for preprocessing of PQ disturbances in [8]. The choices for size of window affect both the frequency and time resolution when using STFT.

In order to overcome the limitations of both FT and STFT, WT has been widely used for analyzing the PQ problems [9]. For detection of voltage sag, wavelet transform (WT) is used [10]. In [11] S-Transform and TT-Transform are used for the purpose of feature extraction of the signal. And Probabilistic Neural Network based feature selection (PFS) is used for eliminating the non-essential features and is the combination of the Fully Informed Particle Swarm (FIPS) and an Adaptive Probabilistic Neural Network (APNN) techniques. Results indicate that this optimal feature selection technique improves the performance of the classifiers even in the noisy environment. In [12] authors proposed the Empirical mode decomposition with Hilbert transform for the assessment of the PQ disturbances and a probabilistic neural network as a classifier. In [13] authors presented the EMD with Hilbert transform for feature extraction of voltage sag. Probabilistic Neural Network (PNN) is used as a classifier for classifying these features to identify the cause of voltage sag.

This paper deals with the Hilbert- Huang Transform technique proposed by Huang et al [14]. Hilbert-Huang Transform used for analysis of signal consist of two components: Empirical Mode Decomposition (a decomposition algorithm) and Hilbert spectral analysis (spectral analysis tool) [15]. EMD decompose the signal into a set of functions known as Intrinsic Mode Functions (IMF). IMF is the orthogonal representation of the analyzed signal so HHT will be the appropriate method for non- stationary and non- linear signal analysis. In this paper, Hilbert–Huang transform has been tested on different PQ events. The results are presented here in terms of IMF and Hilbert-Huang spectrum of the signals. After getting the IMFs, Hilbert transform is applied on it and we obtain the Hilbert–Huang spectrum which is the time-frequency-energy representation of the signal. So, one of the advantages of HHT is that it can deal with the large size signals. Generation of PQ events has been done in Power System Laboratory. Proposed algorithm has been tested on real-time to characterize the power quality disturbances to prove the effectiveness and efficiency.

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he paper is organized in four sections. In section I introduction for HHT and other methods are given. Section II presents the mathematical formulation of HHT. In Section III, the effectiveness of HHT is tested by using simulated signals and by the IMFs components, Instantaneous frequency, absolute value, phase and the Hilbert-Huang spectrum. Finally, Section IV lays out the conclusive remarks.

II. Hilbert-Huang Transform

The development of HHT was motivated by the need to describe the non-stationary and non-linear data [14]. Generally most of the natural processes are non-stationary and non-linear. Some of the above discussed transforms are applicable to non-stationary and linear signals and some are applicable to non-linear and stationary signals. HHT is the combination of Empirical mode decomposition and Hilbert transform [16].

A. Empirical Mode Decomposition

EMD is the process that can deal with both non-stationary and non-linear data. As compared to other methods, this method is adaptive and highly efficient. Mono component and symmetric component from the non linear signals are extracted by the Empirical mode Decomposition (EMD) through sifting process [15]. Sifting is the process of removing the lowest frequency information but the highest frequency remains. The main feature of EMD is to decompose a signal into Intrinsic Mode Functions. And the superposition of these IMF components can reconstruct the original signal. The two conditions must be satisfied for a function to be an IMF:
1. The number of extrema and the number of zero-crossings must be either equal or differ by one in the complete dataset.
2. The mean value of the envelope at every point is defined by the local maxima and local minima which are equal to zero.

The sifting process for extracting the IMF from the signal is given below:
1. Determine all the extrema (maxima and minima) points of the signal $x(t)$.
2. Connect all the maxima and minima with cubic spline and construct the upper and lower envelope.
3. Calculate the mean of upper and lower envelop and is denoted by $m_1(t)$.
4. Now subtract the mean $m_1(t)$ from the original signal $x(t)$ to get $h_1(t) = x(t) - m_1(t)$.
5. If $h_1(t)$ satisfies the two conditions of IMF, then is the first IMF component otherwise it is treated as the original signal and the steps (1)-(5) are repeated to get .
6. Now the above sifting process is repeated k times and becomes first IMF component.
7. Calculate the residue.
8. Now consider as the original signal and repeat the step from 1 to 7 and the second IMF is obtained.

The above procedure is repeated n times to get n number of IMFs and the sifting process can be stopped when becomes a monotonic function from which no IMF can be exracted.

After the signal $x(t)$ has been fully decomposed, the finite sum of the IMFs and a final residue is equals to

$$x(t) = r_n(t) + \sum_{j=1}^{n} IMF_j(t) \quad (1)$$

B. Hilbert transform

The Hilbert Transform of a time domain signal x(t) is denoted by e(t), which mainly gives the local properties of $x(t)$

$$e(t) = \frac{P}{\pi}\int_{-\infty}^{+\infty}\frac{s(\tau)}{t-\tau}d\tau \quad (2)$$

where P is the Cauchy's principle value integral. Complexification results are shown as in

$$z(t) = s(t) + ia(t)\,e^{i\emptyset t} \quad (3)$$

Where $$a(t) = [s^2(t) + e^2(t)]^{1/2}, \quad (4)$$

$$\emptyset(t) = \arctan(e(t)/s(t)) \quad (5)$$

$a(t)$ is the instantaneous amplitude of $s(t)$ and $\emptyset(t)$ is the instantaneous phase of $s(t)$.
The instantaneous frequency is simply

$$\omega = \frac{d\emptyset(t)}{dt} \quad (6)$$

Most Power Quality disturbances are non-stationary and hence amplitude and frequency varies with time. Single frequency for such signals cannot be defined and it's representation by unlike sinusoidal signals is also not accurate. This requires a parameter which varies with time hence more flexible and extended approach of frequency is required. This Instantaneous frequency (IF) concept arises for the signal having a single frequency or narrow band of frequencies. This concept helps in Power Quality disturbances which are non- stationary.

Under all conditions, a perfect instantaneous frequency definition is not guaranteed by IMF and is in fact approaching towards the mono-component. Many applications have proved that the instantaneous frequency defined is still possible for an IMF, even under the worst conditions. IMFs represent a simple oscillatory mode as an analogue to simple harmonic function but it is more general rather than constant amplitude and frequency. As in a simple harmonic component, the IMF can have a variable amplitude and frequency as function of time. Practically, most of the signals at any time may hold more than one oscillatory mode means the signal can have more than one instantaneous frequency at a time. Assuming that the data consists of different simple IMFs, and to break down a signal into IMF components the EMD is developed.

After the signal s(t) has been fully decomposed, the finite sum of the IMFs and a final residue is shown as in

$$s(t) = r_n(t) + \sum_{j=1}^{n} IMF_j(t) \quad (7)$$

After obtaining IMF components, Hilbert transform can be applied to each IMF component. After implementing this, the signal can be expressed as in

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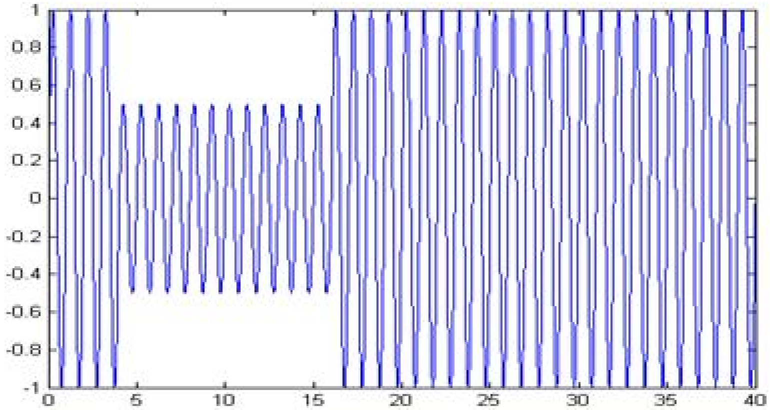

Figure 1. Depicts voltage sag signal.

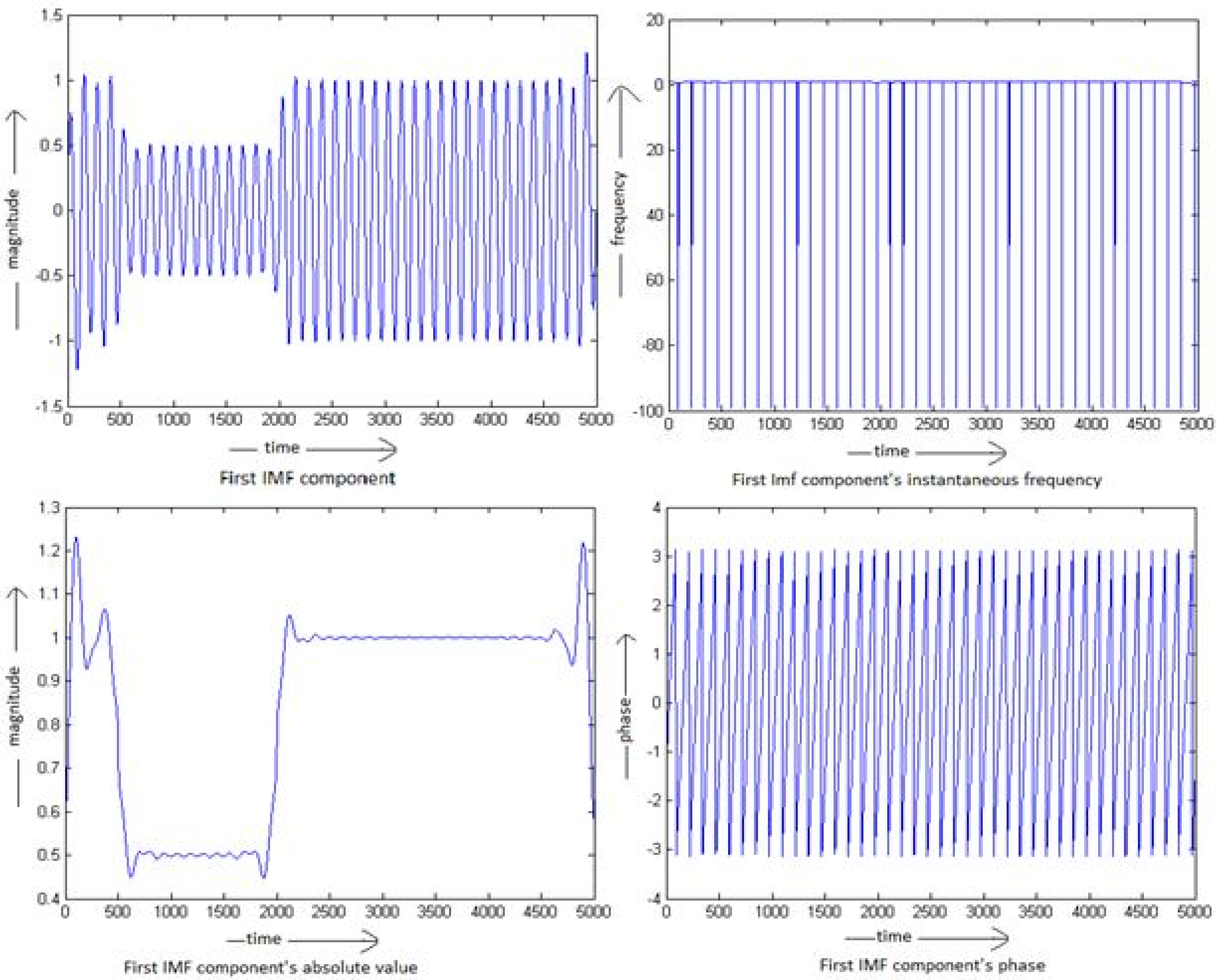

Figure 2. Shows the Hilbert transform of first IMF component

$$s(t) = \sum_{j=1}^{n} a_j(t) exp\left(i \int \omega_j(t) dt\right) \qquad (8)$$

Equation (8) shows IMF represents a generalized Fourier decomposition [17]. Variable amplitude and instantaneous frequency are not only for the better efficiency of the expansion but also they allow the expansion to contain non-linear and non-stationary information. From the expansion of IMF, amplitude and frequency modulations are cleaved. And frequency-time distribution of the amplitude is called "Hilbert amplitude spectrum" H(ω,t) or "marginal spectrum". We can represent the marginal spectrum as $h(\omega) = \int_0^t H(\omega, t) dt$.

III. Case Study Of Power Quality Events

Three cases have been considered here to test the performance of HHT on non-stationary signal: voltage sag, voltage swell and harmonics with sag.

Case1: Voltage sag is shown in fig. 1. Signal is analyzed with the help of HHT which gives the IMF components and residues of the signal. Hilbert transform of first IMF

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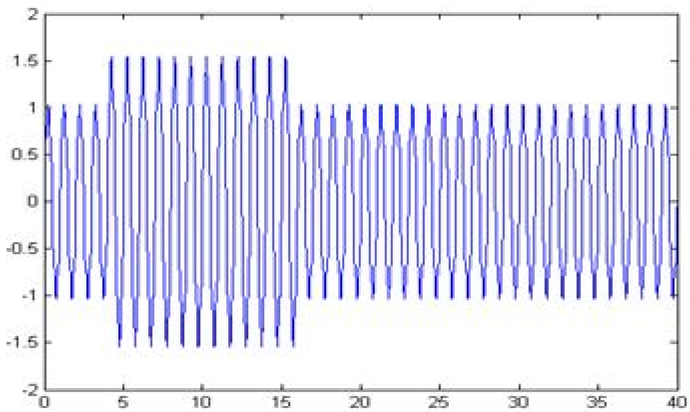

Figure 3. Depicts voltage swell

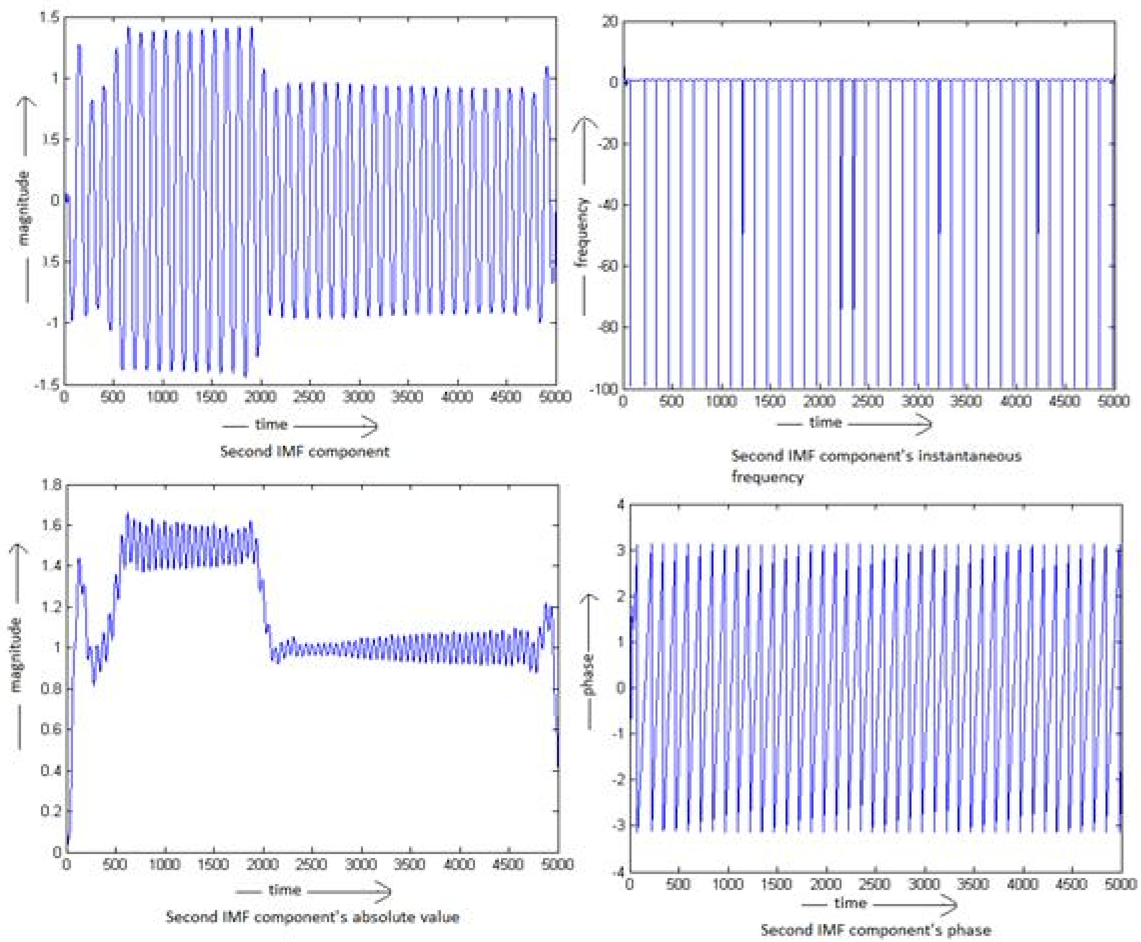

Figure 4. Shows the Hilbert transform of second IMF component

III. Case Study Of Power Quality Events

Three cases have been considered here to test the performance of HHT on non-stationary signal: voltage sag, voltage swell and sag with harmonics.

Case1: Voltage sag is shown in fig. 1. Signal is analyzed with the help of HHT which gives the IMF components and residues of the signal. Hilbert transform of first IMF component that gives instantaneous frequency, absolute value and phase as shown in fig. 2.

Case 2: Voltage swell is shown in figure 3. Signal is analyzed with the help of HHT which gives the IMF components and residues of the signal. Hilbert transform of second IMF component that gives instantaneous frequency, absolute value and phase as shown in figure 4.

Case 3: Sag with harmonics is shown in figure 5. Signal is analyzed with the help of HHT which gives the IMF components and residues of the signal. Hilbert transform of second IMF component that gives instantaneous frequency, absolute value and phase as shown in figure 6.

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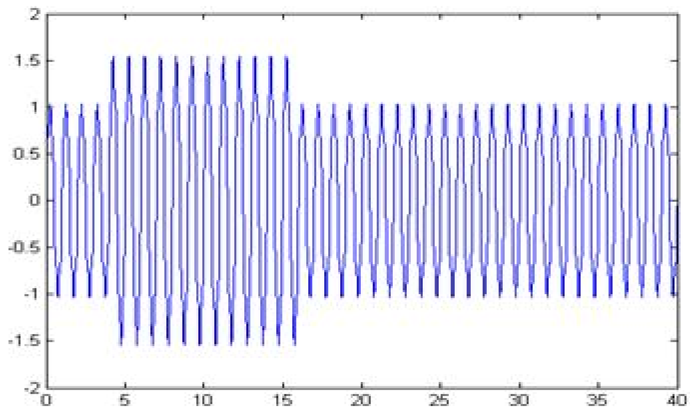

Figure 1. Depicts voltage swell

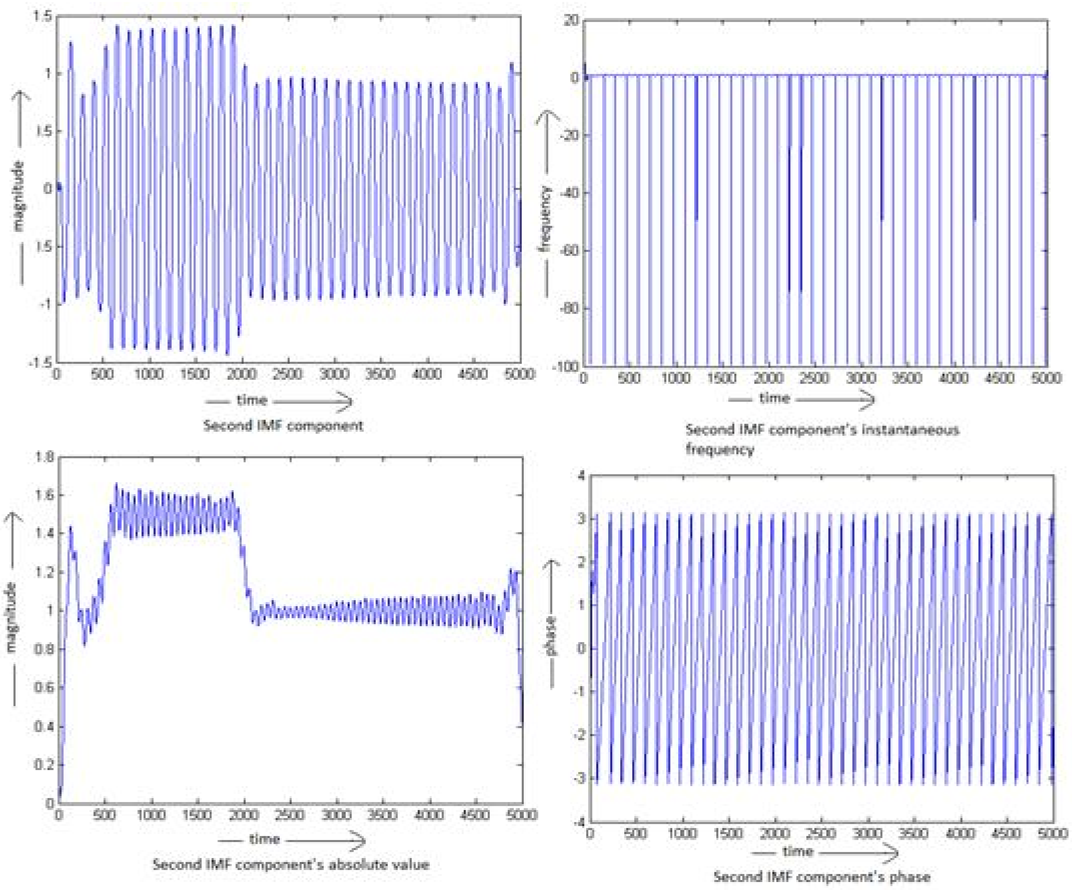

Figure 4. Shows the Hilbert transform of second IMF component

component that gives instantaneous frequency, absolute value and phase as shown in fig. 2.

Case 2: Voltage swell is shown in figure 3. Signal is analyzed with the help of HHT which gives the IMF components and residues of the signal. Hilbert transform of second IMF component that gives instantaneous frequency, absolute value and phase as shown in figure 4.

Case 3: Harmonics with sag is shown in figure 5. Signal is analyzed with the help of HHT which gives the IMF components and residues of the signal. Hilbert transform of second IMF component that gives instantaneous frequency, absolute value and phase as shown in figure 6.

The above figures show the performance of HHT on the PQ events. First of all EMD is applied on the signal which decompose the signal into mono-components known as IMF. Upper IMF components contain highest frequency information and it is lower down as we move towards last component of IMF. We have tested all IMF components by applying Hilbert transform on these IMFs but in this paper we have consider only two IMFs because most of the information lies in first three IMF components. The advantage of this method is that it does not require predetermined set of mathematical functions and it allows projection of a non stationary signal onto a time frequency plane using a mono component signals, thus making it adaptive in nature. Also it can easily extract the features from the signal of large size

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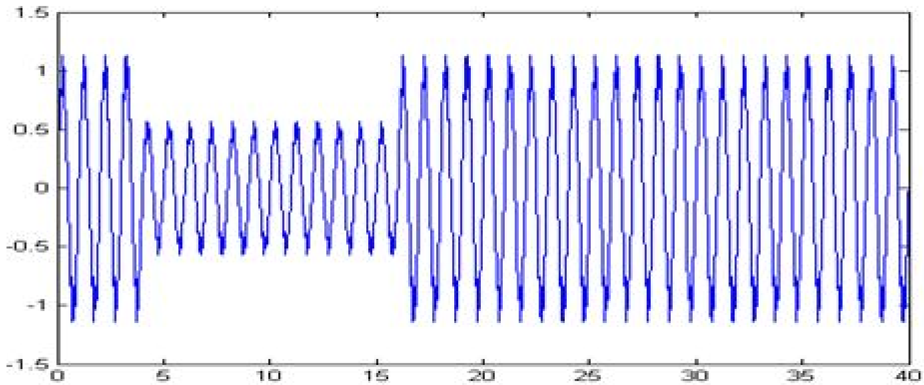

Figure 5. Depicts harmonics with sag

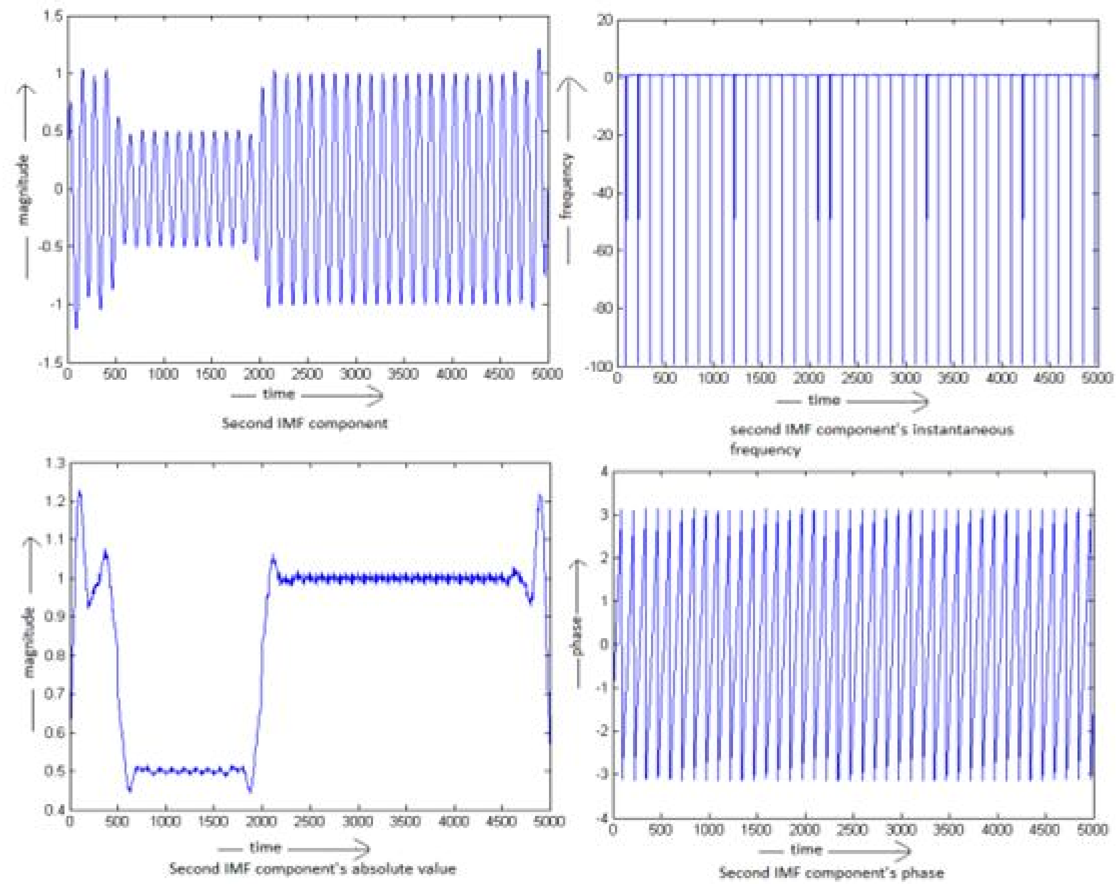

Figure 6. Shows the Hilbert transform of second IMF component

because its EMD operation does not involve the convolution and other time consuming operations. Frequency resolution and the time resolution concept are not taken in the Hilbert-Huang spectrum but the instantaneous frequency is used. This indicates that HHT is an impressive and efficient way for the time frequency analysis of non linear and non stationary data.

IV. Conclusions

In this paper, HHT is implemented on single and multiple PQ events. HHT is the combination of EMD and HT. EMD decomposes the input signal into intrinsic mode functions and first two IMFs give the true frequency content in the signal. After getting IMFs, HT is applied on the IMFs and instantaneous frequency, absolute value, phase has been obtained. And if there is some change in the input signal then there will be drastic change in the absolute value and less change in the instantaneous frequency and no change in the phase as shown in the results. So the analysis of the entire signal considered shows the dominating components in the spectrum. From this study, it has been proved that HHT performs better than the time resolution and frequency resolution based methods and the results justify this statement.

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